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Effect of coir geotextile and geocell on ephemeral gully erosion in the Mollisol region of Northeast China

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Abstract: The unique geomorphological features and farming methods in the Mollisol region of Northeast China increase water catchment flow and aggravate the erosion of ephemeral gully (EG). Vegetation suffers from rain erosion and damage during the growth stage, which brings serious problems to the restoration of grass in the early stage. Therefore, effects of coir geotextile and geocell on EG erosion under four confluence intensities were researched in this study. Results of the simulated water discharge erosion test showed that when the confluence strength was less than 30 L/min, geocell and coir geotextile had a good effect on controlling EG erosion, and sediment yield of geocell and coir geotextile was reduced by 25.95%–37.82% and 73.73%–88.96%, respectively. However, when confluence intensity increased to 40 L/min, protective effect of coir geotextile decreased, and sediment yield rate increased sharply by 189.03%. When confluence intensity increased to 50 L/min, the protective effect of coir geotextile was lost. On the other hand, geocell showed that the greater the flow rate, the better the protective effect. In addition, with the increase in confluence intensity, erosion pattern of coir geotextile developed from sheet erosion to intermittent fall and then to completion of main rill, and the protective effect was gradually weakened. In contrast, the protective effect of EG under geocell was gradually enhanced from the continuous rill to the intermittent rill and finally to the intermittent fall. This study shows that coir geotextile and geocell can prevent EG erosion, and the effect of geocell is better than that of coir geotextile on the surface of EG.

Keywords: geocell; coir geotextile; ephemeral gully; confluence intensity; erosion control

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1 Introduction

The harm of soil erosion to the ecological environment and food production has been a concern in many countries (Singer and Warkentin, 1996; Yang et al., 2003; Ollobarren et al., 2016). The ephemeral gully (EG) system occupies an important position in soil erosion, because it is not only the sediment transport channel in EG, but also the sediment transport downhill channel in the whole catchment area, which will have a serious impact on the loss of soil nutrients (Valentin et al., 2005; Chen et al., 2016; Ollobarren et al., 2016). The main cause of EG erosion is microtopography and unreasonable farming methods. Its long-term existence will accelerate soil

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erosion and change the surface slope (Douglas-Mankin et al., 2020; Taguas, 2021). The process of EG erosion is a complex phenomenon, including ditch head tracing erosion, ditch undercut erosion, ditch wall collapse, and expansion erosion (Street and Quinton, 2001; Zheng et al., 2016). Most previous studies have mainly focused on EG erosion models, and the influencing factors of EGs (rainfall, confluence intensity, slope, slope length, surface vegetation, etc.). The impact of EG erosion on soil quality, crops, and the management of EG measures are relatively weak (Liu et al., 2013). Knowing what effective measures to take to control EG erosion is of great significance to the protection of cultivated land resources.

According to the "China Soil and Water Conservation Bulletin 2022", the Mollisol region in Northeast China by 2022 is 21.5×10^3 km^2, accounting for about 19.45% of the total land area, which is 1.18% lower than that in 2021. However, the implementation of the National Black Land Protection Project (2021–2025) shows that the trend of degradation of black cultivated soil has not been curbed, soil erosion of sloping land is still heavy, and the problems of tilling layer thinning and erosion gully are still prominent. Because the control effect of soil erosion in northeastern black soil area is related to grain productivity, it is of great significance to find suitable engineering measures to support soil erosion control.

The Mollisol region in Northeast China is a geomorphological area of overflowing rivers and hills, and the slope is generally gentle. The main tillage method in this area is ridge farming. Through actual investigation, we found that a single ridge farming measure rarely appears in the same area, and longitudinal ridge tillage and horizontal ridge tillage usually exist simultaneously (Xu et al., 2018). Some scholars believe that most of EGs in the black soil area of Northeast China occur on the slope of horizontal ridge or near the horizontal ridge tillage, and there is no EG erosion in longitudinal ridge tillage (Shen et al., 2005; Cui et al., 2007). Poesen et al. (2003) also believed that EGs generally developed at the low-lying waterline of slope surfaces and were significantly affected by microtopography. Hu et al. (2009) found that the main reason for EGs in the black soil area is that at the intersection of longitudinal ridges and horizontal ridges, the runoff in the furrow gathers at the low-lying waterline, and the water overflows after filling the furrow. Because of the high water potential, in addition to the runoff carried, mud and sand continue to accumulate in low-lying places, causing the ridge to collapse quickly. Later, due to the confluence in catchment area, shear stress of water flow is greatly enhanced, and EGs begin to develop. The above research shows that EGs in the black soil area of Northeast China are formed by the collapse of ridges and furrows and have their own unique way of producing and aborting sediment. Confluence plays an important role in the formation and development of EGs (Wu et al., 2019). Concentrated flow causes strong scour in EGs and may cause gully erosion. Wu et al. (2019) found that the main methods of EG erosion are undercut erosion and trace back erosion. Therefore, strengthening the protection of EG bottom can effectively control the further development of EG erosion.

Coir geotextile and geocell are widely used in soil erosion control because of their ability to reduce water flow energy and slope erosion in China. In North America and Europe, wood residuals and chips are commonly used as stabilization measures, especially for soil erosion control on slopes after fires (Prats et al., 2016; Girona-García et al., 2023; Lucas Borja and Zema, 2023). These measures are mainly to reduce soil erosion and increase water infiltration, but they cannot guarantee continuous erosion control on the slope (Table 1). Coir geotextile and geocell are good at preventing undercut erosion and continuous erosion prevention because of their special structures. The functional mechanism of coir geotextile is that the fibers in the lower layer of coir geotextile can combine with surface soil, forming a fiber-soil composite and enhancing the drapability and anti-corrosion ability of soil (Mitchell et al., 2003; Sutherland and Ziegler, 2007). The geocell can divide the surface soil into a network structure, restrain soil laterally, increase the friction between geocell and soil, reduce water flow velocity, and weaken water flow carrying capacity (Yang and Wang, 2004; Wang et al., 2023). Due to the complex honeycomb structure, geocell-soil composites are considered soil layers with improved strength and stiffness values, which are very beneficial for soil retention (Hegde and Sitharam, 2015; Mehrjardi and Motarjemi,

Table 1 Characteristics of different measures for erosion control

Type	Name	Characteristics of different measures		
		Interception and water storage characteristics	Preventing undercutting erosion	Continuous erosion prevention and control on slope surface
Surface continuous covering measure	Coir geotextile	*	*	*
Surface discontinuous covering measure	Mulch with straw or wood chip	*	-	-
Surface blocking measure	Log erosion barrier and log debris dam	*	-	-
Deep interception measure	Geocell	*	*	*

Note: * indicates that this function is available; - indicates that this effect cannot be achieved.

2018). In addition, coir geotextile and geocell can protect the early growth of vegetation (Vishnudas et al., 2012). Shao et al. (2014) showed that coir geotextile can reduce the erosion of surface soil and protect grass species from runoff. Yang and Wang (2004) believe that geocell can alleviate the kinetic energy of water flow, promote sediment settling in the cell, avoid the loss of grass seeds and plant seedlings, and improve the coverage rate of planting grass. The above research shows that both coir geotextile and geocell can reinforce the surface soil, prevent concentrated stream erosion, and protect the germination and growth of plants. However, research on whether there are differences in soil and water conservation benefits between coir geotextile and geocell in EG erosion of farmland is still limited.

Therefore, this study tested the erosion effects of coir geotextile and geocell under four confluence intensities in black soil in Northeast China. The objectives were: (1) to quantitatively study the influence of coir geotextile and geocell on runoff and sediment yield in farmland EGs through simulated confluence test; (2) to understand the erosion process of farmland EGs under coir geotextile and geocell measures; and (3) to compare the protection effects of coir geotextile and geocell on EG erosion.

2 Materials and methods

2.1 Materials and equipment

As shown in Figure 1, the test soil pan is an adjustable steel pan with a length, width, and height of 3.00, 2.00, and 0.45 m, and its slope adjustment range is 0°–30°. To ensure good drainage during the test, we set a drainage hole with a diameter of 5.00 mm at the bottom of the test soil pan every 10.00 cm in length and 10.00 cm in width. The upper confluence device is composed of a flow supply pipe, flow counter, and overflow tank. The flow rate is regulated by the pipeline valve at the flow supply pipe, and the flow rate should be calibrated before each experiment. The experimental soil was collected from a typical cultivated black soil at the 0–20 cm depth in Keshan Farm, Keshan County, Heilongjiang Province, China. The soil used in this study (United States Department of Agriculture Soil Taxonomy): clay (<0.002 mm) content is 6.57%, the silt (0.002–0.050 mm) content is 67.55%, the sand (>0.050 mm) content is 25.88%, the content of organic matter measured by the potassium dichromate-external heating method is 72.95 g/kg, and pH (the ratio of soil to water is 1.0:2.5 with water extraction method) is 6.3.

2.2 Experimental design

In summer and autumn, due to the frequent occurrence of high-intensity rainfall in the black soil area of Northeast China and its special long and gentle slope topography, the erosion effect of inflow on the sloping farmland is increased (Mou et al., 2010; Zheng et al., 2019). This study was based on higher frequency instantaneous rain intensity of 0.71 mm/min in the black soil area of Northeast China (Zhang et al., 1992). Critical catchment area of EGs in the black soil area is 3

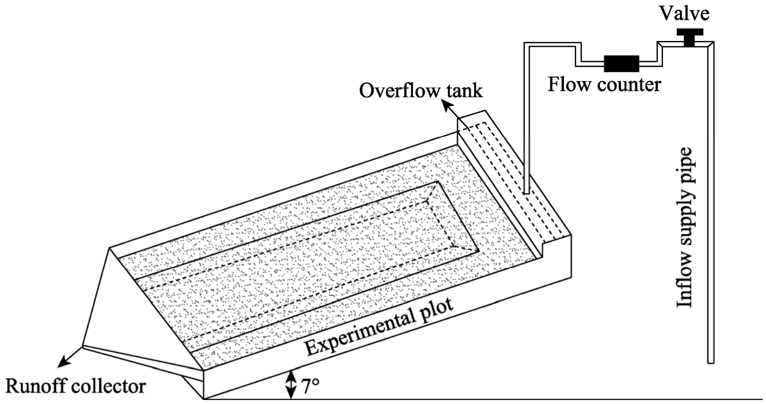

Fig. 1 An illustration of the experimental device. Coir geotextile is made of coconut fiber and a protective net through mechanical processing. Blanket weight is 334 g/m^2, thickness is approximately 3.0–5.0 mm, longitudinal breaking strength is 2.0 kN/m, and transverse breaking strength is 1.9 kN/m. Geocell is made of high density polyethylene material, solder joint peel strength is >3000 N, thickness is 1.3 mm, and height is 60.0 mm.

hm^2, and slope length is 200 m (Hu et al., 2009). According to observed distance (210–270 m) between adjacent EGs in the black soil area (Meng and Li, 2009), we designed upslope inflow rate as 10, 30, 40, and 50 L/min. At the same time, 5°–7° is an important limit for the occurrence of gully erosion in the black soil area of Northeast China (Qin et al., 2014), and due to the influence of microtopography and geomorphology, there are usually microlopes perpendicular to the slope on both sides of EG. Therefore, the test design slope was 7°, and the vertical microslope was 3°. According to the field characteristics of EG morphology measured in the field, prototype EG in this study was designed to ensure the representativeness of EGs in the study area. A scraper was used to scrape out the rudiment of EG at a distance of 30 cm from the top of soil trench. EG trench is located in the middle of the trench. Cross section of the ditch prototype model is approximately trapezoidal (the bottom of the ditch must be leveled before the actual use of coir geotextile), as shown in Figure 2. Scraper for making EG prototype is a 2 m long plank (the same width as experimental soil groove). To ensure the same shape of EG groove prototype, we used the same scraper before the test.

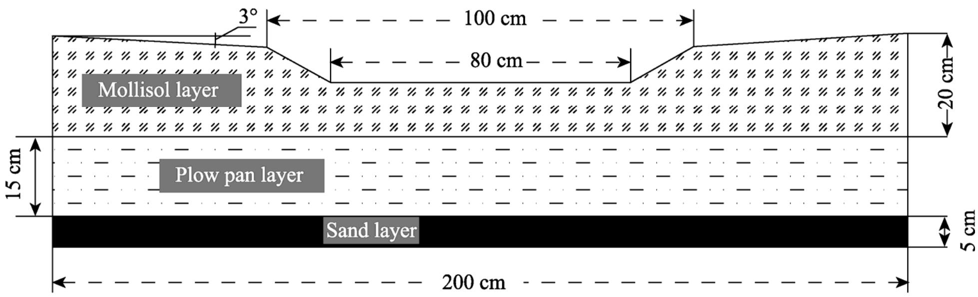

Fig. 2 A cross-section of runoff plot

2.3 Experimental procedure

(1) Geocell measure: the test fill should be treated without grinding, the original structure of soil should be kept damaged, and the shape of test soil should be kept consistent. Before filling the geocell, drainage hole at the bottom of test soil tank was filled with gauze, and bottom of soil tank was filled with 5 cm of fine sand to ensure good water permeability. Then, sand layer was filled with 15 cm of loess and 5 cm of black soil. Bulk density of black soil layer is 1.15–1.20 g/cm^3, and bulk density of loess layer is 1.25 g/cm^3. To ensure the uniformity of filling, we used a rubber

hammer to compact it with a thickness of 5 cm each time. Then, through laying geocell and fixing it on the compacted slope with U-shaped nails (nail length is 15 cm and hook is 5 cm), we calculated filling quality according to the water content of soil. Then, 15 cm of black soil is filled in cell. Finally, soil is compacted to the design height and levelled, as shown in Figure 3.

(2) Coir geotextile measure: first, we filled the drainage holes at the bottom of test soil tank with gauze, and filled in 5 cm high fine sand as a permeable layer. Then, we filled sand layer with a 15 cm loess simulating plow bottom layer and 20 cm black soil as plow layer. Bulk density of plow bottom layer is 1.15–1.20 g/cm^3, and bulk density of plow layer is 1.25 g/cm^3. Before each filling of test soil tank, we determined soil weight needed for each layer by measuring soil moisture content combined with bulk density. After slope was flattened, we made an EG model with a scraper 30 cm away from the top and then covered with a coir geotextile to completely cover the entire EG. When laying, we used U-shaped nails (nail length is 5 cm and hook is 2 cm) from EG. The bottom of ditch was fixed at intervals of 1 m to prevent displacement and ensure good contact between coir geotextile and ground. At the same time, both sides and the top of coir geotextile were buried in soil and compacted, as shown in Figure 4.

(3) To ensure that the initial conditions of each test are basically the same, we carried out a 30 mm/h pre-rainfall the day before the test. When soil surface is fully saturated and will produce runoff, the rainfall is stopped, and soil tank is covered with a plastic sheet. The formal test was conducted for 12 h, and soil moisture content changed from 19.3% to 20.5% in the early stage of the test. Before and after the test, discharge inflow rate is calibrated, and scour test can only be carried out when error between catchment upslope inflow rate and design inflow rate is within 5%. At the same time, three targets were placed as control points on both sides of soil tank, each control point was separated by 1 m, and a Sony ILCE-6000 (Sony Group Corporation, Tokyo, Japan) camera was used to collect photos before and after the test. Overlap rate of photos is more than 70%–80%. After the test started, water flow overflowed to slope surface to start timing, and when there was runoff outflow from collecting port, runoff time was recorded. After runoff was generated, a 20 L plastic bucket was used to take a runoff sediment sample every 2 min. Sampling time was 20 s each time, and the whole test process lasted 45 min. While sampling, we used dye tracer method to measure flow velocity and temperature of shallow ditch runoff. After the test, sediment samples were all weighed. After standing for clarification, we poured supernatant out, and transferred sediment to an aluminum box. Then, samples were dried in an oven at 105°C, weighed, and calculated the quality of sediment.

Fig. 3 Layout of geocell (a) and expanded geocell (b)

Fig. 4 Layout of coir geotextile (a) and expanded coir geotextile (b)

2.4 Data analysis

Photos used Agisoft Metashape v.1.5.2 software to realize three-dimension reconstruction processing of EG erosion. Data processing steps included establishing a sparse point cloud model and generating a dense point cloud model and digital elevation model (DEM) output. The resolution of acquired DEM data was 0.3 mm/pix. Then, using ArcGIS v.10.8, we performed raster processing, such as clipping, subtraction, and masking on the DEM. Finally, the obtained slope elevation changes were imported into Excel v.2016 software, and the corresponding grid areas were multiplied to obtain the erosion amount of each group of experiments. Origin v.2017 software was used for data analysis and graphing.

3 Results

3.1 Effects of coir geotextile and geocell on runoff rate and soil loss rate

Under different measures and upslope inflow rates, change in runoff rate with time showed a trend of first increasing and then stabilizing, and runoff initiation time at the outlet decreased with increasing upslope inflow rate (Fig. 5). At the beginning of the test, water content of soil surface was low, which made runoff for infiltration more. With saturation of soil water, runoff rate showed a steady trend after reaching a certain value. Under 10 L/min upslope inflow rate, runoff rates of coir geotextile and geocell gradually increased with time, and average runoff rate of coir geotextile was lower than that of geocell. When upslope inflow rate was greater than 30 L/min, runoff rate of coir geotextile and geocell first increased rapidly, and then stabilized. Average runoff rate was less than that of bare slope and 1.1 times those of coir geotextile and geocell. Under 50 L/min upslope inflow rate, runoff rates of coir geotextile and geocell were almost the same as that of bare slope. This result indicated that the capacity of coir geotextile and geocell to control runoff of EGs was weakened due to the increase in runoff energy under condition of high upslope inflow rate. Therefore, under certain conditions, coir geotextile and geocell can effectively reduce runoff and increase infiltration. When the range is exceeded, coir geotextile and geocell will lose the flow reduction effect. Compared with geocell, when upslope inflow rate was low, coir geotextile had a significant effect on reducing runoff rate. When upslope inflow rate was 10 L/min, runoff rate of geocell was 1.1 times higher than that of coir geotextile.

Soil loss rates of EGs under coir geotextile and geocell generally showed a gradual decline and then tended to reach a steady state when upslope inflow rates were the same. However, as shown

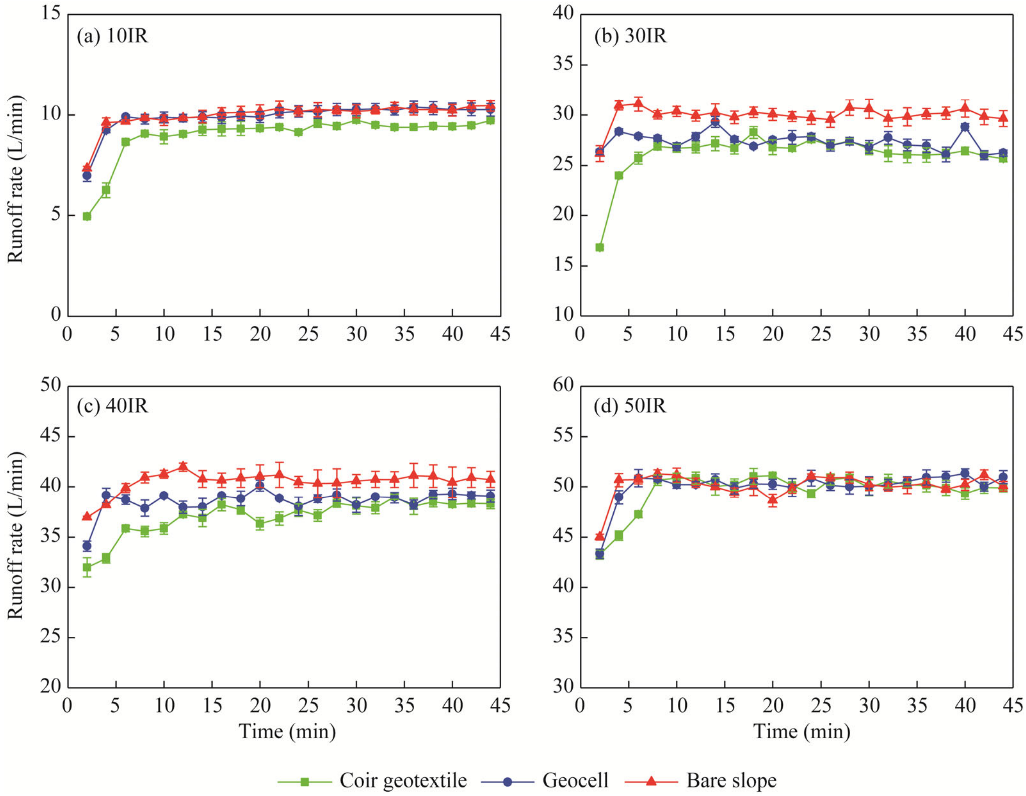

Fig. 5 Variation in runoff rate under different treatments. (a), 10IR (10 L/min inflow rate); (b), 30IR (30 L/min inflow rate); (c), 40IR (40 L/min inflow rate); (d), 50IR (50 L/min inflow rate). Bars are standard errors.

in Figure 6, the greater the upslope inflow rate, the greater the soil loss rate. At the same time, by observing change curve of soil loss rate under different upslope inflow rates, we found that soil loss rate in the first 10 min changed greatly, and with the increase in upslope inflow rate, the curve gradually became steeper. That is, the greater the upslope inflow rate, the greater its impact on soil loss rate. Under 10 and 30 L/min upslope inflow rates, average soil loss rate was in the following order: bare slope>geocell>coir geotextile, and soil loss rate of geocell was 2.8–5.6 times that of coir geotextile. Compared with bare slope, soil loss rate of geocell reduced by 25.95%–7.82%, and soil loss rate of coir geotextile reduced by 73.73%–88.96%. When upslope inflow rate was 40 L/min, soil loss rate of coir geotextile increased sharply by 189.03%, and average soil loss rate was expressed as the following order: bare slope>coir geotextile=geocell. Soil loss rate of coir geotextile was basically the same as that of geocell. Compared with bare slope, soil loss rate of geocell reduced by 21.40%, and soil loss rate of coir geotextile reduced by 41.48%. When upslope inflow rate increased up to 50 L/min, soil loss reduction effect of coir geotextile declined sharply, and average soil loss rate was in the following order: coir geotextile>bare slope>geocell. Soil loss rate of coir geotextile was 1.7 times that of geocell. For bare slope, soil loss rate of coir geotextile increased by 9.98%, and soil loss rate of geocell decreased by 35.37%.

3.2 Erosion amount for EG

Amount of erosion can be used as one of the important indicators for judging the degree of erosion, that is, the greater the amount of erosion, the deeper the degree of erosion, the worse the protective effect of this measure, and vice versa. When upslope inflow rate increased from 10 to 50 L/min, amount of soil erosion in bare slope increased by 1.3 times, 1.7 times in geocell, and 10.5 times in coir geotextile (Table 2). Compared with bare slope, under the same upslope inflow rate, erosion reduction rate of coir geotextile was up to 89.60%, and protection effect was the

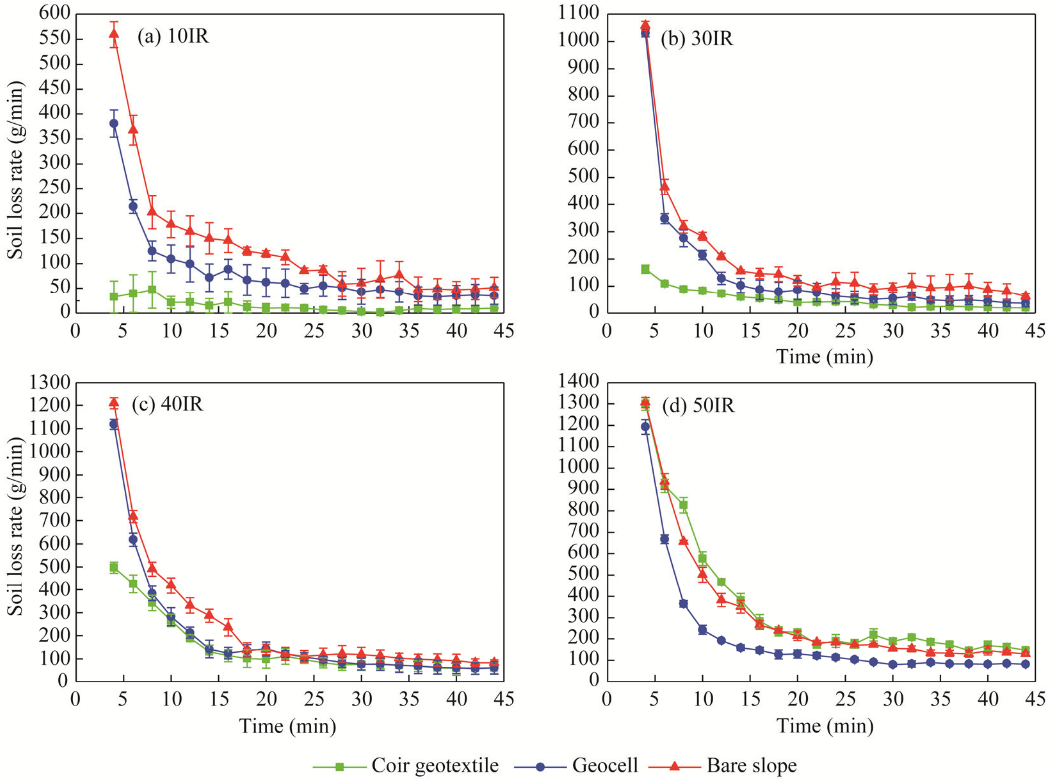

Fig. 6 Variation in soil loss rate under different treatments. (a), 10IR (10 L/min inflow rate); (b), 30IR (30 L/min inflow rate); (c), 40IR (40 L/min inflow rate); (d), 50IR (50 L/min inflow rate). Bars are standard errors.

Table 2 Soil loss and erosion reduction effectiveness under different treatments

Treatment	Soil loss (g)				Erosion reduction effectiveness (%)			
	10IR	30IR	40IR	50IR	10IR	30IR	40IR	50IR
Bare slope	8931	9014	11,102	11,962	-	-	-	-
Geocell	3633	5165	5524	6169	59.32	42.70	50.24	48.43
Coir geotextile	929	3894	5680	9770	89.60	56.80	48.84	18.32

Note: 10IR, 10 L/min inflow rate; 30IR, 30 L/min inflow rate; 40IR, 40 L/min inflow rate; 50IR, 50 L/min inflow rate. - means no value.

best, but as upslope inflow gradually increased, reduction rate gradually decreased. Under 50 L/min upslope inflow rate, erosion reduction rate of coir geotextile was only 18.32%, and protection effect was far inferior to that under low upslope inflow rate. Erosion reduction rate under geocell was less than that of coir geotextile when upslope inflow rates were 10 and 30 L/min, which were 59.32% and 42.70%, respectively, but as upslope inflow rate increased, reduction rate was maintained at approximately 50.00%, which was 48.84% and 18.32% higher than those of coir geotextile, respectively.

3.3 Impacts of coir geotextile and geocell on morphological characteristics of EG

EG protected by these two measures shows different erosion morphologies under different upslope inflow rates (Fig. 7). Under 10 L/min upslope inflow rate, the role of geocell was not highlighted. Surface of EG formed a rill that penetrated entire slope, and the maximum erosion depth was 10 mm. There are some patchy deposits in the middle of EG, and deposition thickness was 0–5 mm. However, the surface of EG under the protection of coir geotextile hardly suffered from serious erosion, and overall appearance was micro-erosion in the upper part and

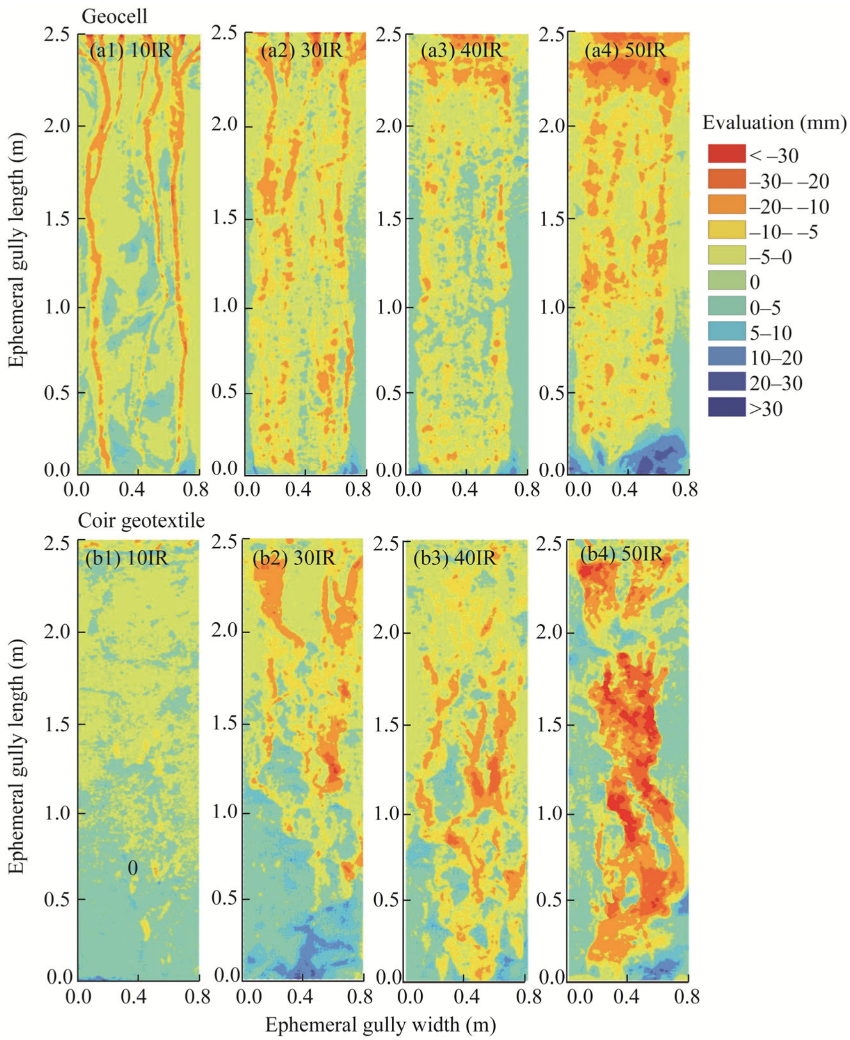

Fig. 7 Microtopography change under geocell (a1–a4) and coir geotextile (b1–b4) treatments. 10IR, 10 L/min inflow rate; 30IR, 30 L/min inflow rate; 40IR, 40 L/min inflow rate; 50IR, 50 L/min inflow rate.

micro-sediment in the lower part of EG. When upslope inflow rate was 30 L/min, due to the barrier of geocell, the integrity of water flow was destroyed, and some intermittent discontinuous rills were formed on the surface. However, under coir geotextile, the middle and upper parts of EG had intermittent sags, and a large amount of sediment was deposited in the lower part, with the maximum deposition thickness reaching up to 10–20 mm. When upslope inflow rate was 40 L/min, the effect of geocell was better reflected. There were no obvious rills on the surface of EG, and only serious erosion occurred on the upper part of EG. However, EG surface under coir geotextile sags increased and some of sags connected, forming intermittent rills. Under this condition, the protective effect of geocell on EG was greater than that of coir geotextile. Under 50 L/min upslope inflow rate, protective effect of geocell on EG was relatively good. With the increase in upslope inflow rate, energy dissipation and obstruction effects of geocell on runoff were obvious, and carrying capacity of water was reduced. Many discontinuous sags formed on the surface of EG, and most severely eroded area still occurred in the upper part of EG. However, a larger and longer rill formed on the surface of EG under coir geotextile. Under the effect of traceable erosion, rill continued to deepen and widen, and eventually developed into a complete network of rills, which made the coir geotextile lose its protective effect. And average erosion depth was 20–30 mm. In summary, it can be seen that with the increase in upslope inflow rate, the

role of geocell was more obvious, and the rill on the surface of EG formed the stronger resistance and had a better anti-erosion effect. The role of coir geotextile was opposite. The higher the upslope inflow, the more serious the surface erosion of EG. Moreover, longer and deeper rills formed and resulted in worse anti-scouring effect. However, under low upslope inflow rate, coir geotextile blocked the flow and had an obvious energy dissipation effect. Erosion occurred above the ditch, and deposits formed below.

4 Discussion

4.1 Effect of coir geotextile and geocell on erosion

Studies have shown that upslope inflow plays an important role in EG erosion (Li et al., 2016; Wang et al., 2023). Under different upslope inflow rates, the protective effects of coir geotextile and geocell on EGs were quite different. The results of this study showed that when upslope inflow rate was less than 30 L/min, soil loss rate of coir geotextile was reduced by 73.73%–88.96%. Average runoff rate and soil loss rate were lower than those of geocell, especially when upslope inflow rate was 10 L/min, and soil loss rate of coir geotextile was the smallest. When upslope inflow rate increased up to 40 L/min, the runoff rate and soil loss rate of coir geotextile were not much different from those of geocell, and its protective effect decreased. When upslope inflow rate continued to increase up to 50 L/min, runoff rate and soil loss rate of coir geotextile exceeded bare slope, and the function of protecting EG was completely lost. Won et al. (2012) found that coir geotextile coverage within a certain range could reduce or even prevent erosion. Zheng et al. (2020) also suggested that once the protective effect of ecological measures reached a certain level, these measures would no longer be a factor restricting slope erosion. This phenomenon can be attributed to the structure of coir geotextile, which is fixed on the bottom surface of EG by U-shaped nails. When upslope inflow rate is low, coir geotextile can increase the surface roughness, causing the local water flow to form turbulence, reducing flow velocity and weakening water flow (Rickson, 2006; Sutherland and Ziegler, 2007). However, when upslope inflow rate is high enough, the friction force increased by coir geotextile is less than shearing force of runoff, and soil loss rate will increase sharply and lose its protection effect. In contrast, the higher the inflow rate, the more obvious the protective effect of EG for geocell. Runoff only washes the surface soil of geocell, but with the increase in upslope inflow rate, the exposed geocell hinders water runoff and changes the direction of runoff. To a certain extent, the kinetic energy of runoff weakened.

At the same time, geocell can effectively reduce the amount of EG erosion. With the increase in inflow rate, erosion intensity and total erosion effect of EG will increase simultaneously, and the reduction ratio of erosion amount will decrease. In this study, reduction rate of EG erosion of geocell was relatively stable, which showed that the performance of geocell in reducing erosion intensity was more fully reflected with the increase in upslope inflow rate. The erosion reduction rate of coir geotextile suddenly decreased with increasing upslope inflow rate. Moreover, erosion reduction rate of low upslope inflow rate was higher than that of geocell, and erosion control effect was obvious. Erosion reduction rate of high upslope inflow rate decreased rapidly, which indicated that the performance of coir geotextile to reduce erosion strength decreased with the increase in upslope inflow rate. Therefore, the protection effect of coir geotextile under low upslope inflow rate was better than that of geocell, while protection ability under high upslope inflow rate was lower than that of geocell, and the protective effect of geocell was more stable.

4.2 Erosion morphology of coir geotextile and geocell

Coir geotextile and geocell seriously affect the process of EG erosion-sedimentation. Under different upslope inflow rates, morphological characteristics of EG were quite different. Under coir geotextile, erosion morphology of EGs from low to high upslope inflow rate was slightly flaky erosion, then intermittent sags to intermittent rills and finally developed into continuous main rills, of which the maximum erosion depth was roughly between 20 and 30 mm. In contrast,

erosion pattern of EG under geocell was opposite. From continuous rills to intermittent rills and finally to intermittent sags, the greater the inflow rate is, the more seriously the surface of EG will be broken. The reason of the result is related to the protection mechanism of these two measures. Fiber layer of coir geotextile can be combined with the surface soil of EG to form a fiber-soil complex, forming many micro-landforms under low upslope inflows and increasing the surface roughness and corrosion resistance (Mitchell et al., 2003). With the increase in upslope inflow rate, water flow forms direct runoff on the surface and inside of coir geotextile, which increases the erosion intensity of runoff (Liu et al., 2019). The fiber-soil complex is not enough to resist the shear force of runoff, which causes EG surface to form larger and longer rills and results in more severe erosion. Geocell divides the surface soil at the bottom of EG into independent small cells, but these small cells form an organic whole through binding effect of geocell. Therefore, geocell has a certain degree of erosion resistance and stability when concentrated water flow is scoured. It is difficult to form a fixed flow path, thereby reducing the erosion of EG (Zeng et al., 2017). In summary, coir geotextile can be used to protect the surface of EG at a certain inflow rate, and geocell can prevent the spatial erosion of EG at high upslope inflow rate.

In addition, whether geocell is under low upslope inflow or high upslope inflow or not, the erosion at the bottom of EG is relatively uniform, i.e., no obvious local erosion is observed, no large gully is formed, and erosion is more evenly distributed along the bottom of EG. Wang et al. (2021) found that geocell played a role in restraining surface soil deformation, and its erosion method was mainly laminar erosion, which could prevent the erosion from evolving into gully erosion. However, coir geotextile is dominated by a chip eclipse under a low upslope inflow rate, which can play a better role. As upslope inflow rate increases, obvious gully erosion will occur at the bottom of EG. Sutherland and Ziegler (2007) showed that surface coverage provided surface roughness, which directly impacted sediment transport relationship. Ideally, an effective erosion control system should prevent the transition from an interrill (splash and wash)-dominated transport surface to an incised rill-dominated transport surface, even in high upslope inflow rate events. Therefore, coir geotextile is not as stable as geocell in protecting against EG erosion. In farmland EG management, coir geotextile and geocell can be considered together. On the one hand, they can reinforce soil, stabilize EG soil, and play an important role in soil and water conservation; on the other hand, they can improve soil structure to ensure the growth of vegetation at the early stage during growth period.

4.3 Research limitation and future prospective

From the results of this study, it can be concluded that erosion protection effect of coir geotextile under high upslope flow rate is not as good as that of geocell. In the future application process, people should select appropriate measures according to local environmental conditions, or the two measures can be applied simultaneously to give full play to their respective advantages. The limitations of this study lie in its focus on studying runoff in simulated runoff plots rather than conducting field research and the lack of long-term on-site observational data to verify the long-term effects in actual environments.

Application of these two measures could involve in the following aspects. First, the research indicates that at a flow rate of 50 L/min, the protective efficacy of coir geotextile gradually diminishes, even ceasing to function, which could be the focal point for further research. For example, how to improve the protective effect of coir geotextile under high velocity, or based on the characteristics of critical flow rate, is important to determine the application area of coir geotextile to achieve better soil erosion control. Second, the study found that in the black soil area of Northeast China, the occurrence of undercutting erosion had increased and exacerbated the erosion amount of gullies due to the special black soil type and agricultural cultivation methods. Given the soil erosion characteristics of black soil area, future research should continue to explore more durable and stable low-cost measures. Last, expanding the research scope in the future to explore the applicability and effectiveness of measures under soil conditions in different areas could facilitate the development of more precise prevention and control strategies.

5 Conclusions

This research aims to explore the control effect of coir geotextile and geocell on farmland EG erosion by simulating upslope inflow rate, and compare DEM before and after the test to calculate the amount of soil erosion in EG. The results showed that: (1) the protective effect of coir geotextile under low upslope inflow rate was better than that of geocells, while the protection capacity under high upslope inflow rate was lower than that of geocells; (2) the protective effect of geocell was more stable than that of coir geotextile. With the increase in upslope inflow rate, the erosion reduction rate of geocell changed little, while erosion reduction rate of coir geotextile decreased rapidly; and (3) with the increase in upslope inflow rate, the morphology of EG developed from sheet erosion to a complete main rill, and the maximum erosion depth was between 20 and 30 mm under coir geotextile. Under geocell, the morphology of EG developed from continuous rills to intermittent rills and finally to intermittent sags, and the erosion rate was lower than that of bare slope. From the erosion reduction rate, the treatment of geocell at the bottom of EG is better than that of coir geotextile.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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